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NAVAL AIR DEVELOPMENT CENTER

WARMINSTER, PA. 18974

REPORT NO. NADC-73155-30 12 Jul 1973

AN EVALUATION OF THE NEED FOR DECK MOTION PREDICTION ON THE WAVE-OFF ADVISORY SYSTEM

FINAL REPORT
AIRTASK A320-5301/202B/2F00-421-204
WORK UNIT NO. 1

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DEPARTMENT OF THE NAVY
NAVAL AIR DEVELOPMENT CENTER
WARMINSTER, PA. 18974

AIR VEHICLE TECHNOLOGY DEPARTMENT

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A statistical model of the carrier wave-off situation is developed using experimentally measured data for carrier deck motion and aircraft approach geometry. This model is used to estimate the effect of ramp motion on the operation of the WOAS (Wave-Off Advisory System). In this manner the performance gains that could be achieved by adding a Deck Motion Prediction System to the WOAS are evaluated.

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SUMMARY

An investigation of the need for adding a DMP (Deck Motion Prediction) System to the WOAS (Wave-Off Advisory System) is reported herein. A statistical analysis of aircraft wave-off trajectories was performed to determine whether it was necessary to compensate for aircraft carrier deck motion in order to improve the operation of the WOAS. A logical analytical technique was established in which variations in aircraft initial conditions were used to generate a variation in the amount by which the aircraft would clear the ramp. This method was considered to be a reasonable representation of the variation in wave-off trajectories caused by turbulence and pilot errors. The statistical analysis was developed based on the mean and variance in aircraft approach speed, sink rate, and altitude at a specified range. These statistical data, outlined in references (a) and (b), formed the basis for a matrix of aircraft initial conditions. The initial condition matrix was set up to encompass the range of possible wave-off points. Then wave-off trajectories were computed for each set of initial conditions using the F-8 aircraft equations of motion. Next, a probability of occurrence was assigned to each initial value of airspeed, altitude, and sink rate based on its value relative to the mean. The probability of each case was determined by multiplying together the probabilities of the components of the initial condition. In this way, a probability was assigned to the ramp clearance resulting for each wave-off. All of the cases were then combined to form a non-pitching deck ramp clearance distribution. This ramp clearance distribution served as a basis for evaluating the effects of ramp motion.

For purposes of analysis it was assumed that the WOAS was completely accurate when the deck was not pitching, but that it had no capability of correcting for ramp motion. Therefore, errors in the actual ramp clearance would exist in an amount equal to the displacement of the ship between the time that the wave-off was executed and the instant the aircraft crossed the ramp. Statistical data on the aircraft carrier ramp motion were used to evaluate the magnitude and probabilities of any errors in the ramp clearance predicted by the WOAS.

This analysis showed that large ramp motions produced sufficient errors in the WOAS to make a compensation scheme desirable. A technique of correcting for ramp motion by biasing the wave-off boundary upward was investigated. However, the amount of bias required was found to be excessive. Therefore, it appeared that some alternative method should be developed to improve the operation of the WOAS. Since no other proposals for remedying the deck motion problem currently exist, it was recommended that the deck motion prediction system technique be further investigated.

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LIST OF SYMBOLS

Symbol	Description	Dimension
STI	Systems Technology, Inc.	-
X	Incremental altitude considered in ramp clearance statistics	ft.
$\bar{X}$	Mean value of a general statistical quantity	-
σ	Variance of any statistical quantity	-
σX	Variance of a general statistical quantity X	-

I. INTRODUCTION

The WOAS is being developed to assist the LSO (Landing Signal Officer) in determining the last safe point a wave-off may be executed in order to prevent a landing accident. This system incorporates a trajectory prediction algorithm stored in the SPN-42 Automatic Carrier Landing System digital computer. Aircraft range and altitude and wind over the deck are supplied to the computer. This information is used to continuously calculate the trajectory that the airplane would follow if it waved-off at each point along its approach flight path. Approximately twenty complete wave-off trajectories are computed each second. In this way, the ramp clearance is computed during the approach and the result is presented to the LSO. When the predicted ramp clearance falls below a safe level, a wave-off signal is flashed to the LSO.

One possible limitation of the WOAS arises because the system does not account for deck motion. If the deck is pitching up, the wave-off command might not be given soon enough to prevent a ramp strike. Alternatively, if the deck were pitching down, a premature or unnecessary wave-off might be ordered. Several deck motion prediction systems have been proposed for use with the WOAS. However, there has been no quantitative evaluation to determine the gain that might be achieved by adding these systems. Therefore, this study was undertaken to determine the seriousness of ramp motion induced errors in the WOAS.

II. ANALYSIS

A statistical model of the carrier approach and wave-off situation was created to evaluate the effect of ramp motion on the operation of the WOAS. The approach, as outlined in figures 1 and 2, was to assume a normal distribution of aircraft initial approach conditions. Then, wave-off trajectories were calculated based on these initial conditions to form a baseline statistical distribution of ramp clearances. For purposes of analysis it was assumed that the WOAS gave perfect prediction when the deck was not pitching, and that all errors in the system resulted from deck motion. Experimentally derived deck motion statistics were introduced to determine the magnitude of the error in the predicted ramp clearance that would result if the WOAS had no deck motion prediction capability. Then the magnitude of these errors was used as a basis for deciding on the importance of further modification of the WOAS.

Because aerodynamic and control characteristics were readily available for the F-8, this aircraft was selected as a representative carrier aircraft for the analysis. The aircraft dynamics were modeled as described in reference (d). Then the Terminal State

Predictor algorithm which is used in the WOAS was used to compute the distance by which the aircraft would clear a non-pitching deck. Elevator and thrust input commands remained invariant throughout the investigation. As a result the only differences in the trajectories investigated were their initial altitude, sink rate, and air speed. Therefore, the ramp clearance was only a function of these initial conditions.

An approach scenario was established in which wave-offs were executed beginning with a variety of initial values of altitude, sink rate and airspeed. All of the wave-offs were executed at a point 910 feet from touchdown. This point was selected because it is the last point at which an automatic wave-off can be given by the SPN-42 system. The range limitation is established by the degradation in radar accuracy close to the ship. In actual operation the WOAS is designed to issue a wave-off at a range calculated to guarantee 10 feet of ramp clearance. However, the effect of ramp motion is more easily analyzed by fixing the range for wave-off. Instead of determining the wave-off point to provide 10 feet of ramp clearance, the range was fixed and the variation in deck clearance was calculated.

Experimental data collected from carrier approaches by A-7 and F-4 aircraft were used to define the variances in approach airspeed, sink rate, and altitude. Data for the altitude dispersion were derived from reference (a). Touchdown data from reference (b) were used to determine the variance in airspeed and sink rate. These data were assumed to hold over the range from 910 feet to touchdown because the pilot control task and the approach environment remain nearly constant over that distance. Since equivalent data for the F-8 aircraft were not available, the A-7 and F-4 variances were applied to the F-8. It was reasoned that the F-8 which has similar response characteristics to those of the F-4 and A-7 should have similar variances in the approach conditions.

Since the mean values of the F-8 airspeed, sink rate, and altitude were available from reference (d), these were combined with the assumed variances to specify the statistics of the F-8 approach conditions.

A matrix of initial values of altitude, airspeed, and sink rate was constructed by including all combinations of these three variables covering a range from -3σ to $+3\sigma$ about the mean for each variable. This range was selected because it covered 99 percent of a normal distribution. Seven values of each variable were selected to uniformly cover this range. Therefore, a total of $7^3 = 343$ combinations of initial conditions were established. The mean and variances of the initial conditions are summarized in table I which is based on data from references (a) and (b).

The probability of each component of the initial conditions was determined by its location with respect to the mean value on a normal distribution. The overall probability of a given initial condition was determined by multiplying together the probabilities of the three components.

A steady deck ramp clearance distribution was determined for the selected initial conditions by calculating the steady deck ramp clearance for each case and assigning a probability to each trajectory based on its initial conditions. The steady deck distribution was constructed by dividing the ramp clearance range into a number of segments. All of the aircraft trajectories were sorted into their respective ramp clearance ranges and the probabilities of all of the cases in each segment were added to form an overall distribution. This non-pitching deck ramp clearance distribution, illustrated by figure 3, forms a baseline for evaluating the effects of ramp motion. The statistics used for comparison purposes are the probability that the aircraft will strike the ramp and the probability that it will clear the deck by 10 feet or less. <u>The amount by which these two quantities increase when ramp motion is introduced provides a measure of the significane of ramp motion.</u>

The effects of ramp motion were evaluated by using carrier motion data derived from reference (c). Two distributions having maximum amplitudes of 12 feet and 20 feet respectively were selected to represent normal operational conditions. A third case representing more moderate sea states was derived by scaling the 12 foot case to 6 feet amplitude. The 12 foot and 20 foot distributions are illustrated by figures 4 and 5. The ramp clearance distribution with deck motion present was computed by calculating the statistical distribution for the difference between aircraft altitude at the ramp and ramp displacement. This was computed for all three ramp motion distributions.

To accomplish this, both the aircraft altitude distribution and the ramp motion distributions were divided into discrete segments. The probabilities of all combinations formed by taking one segment from the aircraft altitude distribution and one segment from the ramp distribution were computed. Then all the computed probabilities corresponding to a given range of values for the difference in aircraft altitude and ramp displacement were added. This procedure produced a new statistical distribution which described the aircraft altitude relative to the moving ramp. These distributions are illustrated in figures 6 to 8. In addition the distributions are summarized in tables II to V.

Examination of the ramp clearance distributions showed that deck motion introduced a significant error into the predicted ramp clearance. The probability of striking the ramp or of clearing the deck by less than 10 feet increased dramatically as the magnitude of the deck motion increased. An attempt to correct this problem was made by using a bias system. Under this scheme the wave-off boundary would be elevated above the 10 foot level established for a non-pitching deck. Each of the moving deck ramp clearance distributions was analyzed to determine how much the boundary would have to be raised to eliminate the chance of a ramp strike. A point on each deck clearance distribution was established where the percentage of passes falling to the left of that point was the same as the percentage of passes on the steady deck distribution which failed to clear the ramp. The distance that this point fell to the left of zero on the moving deck clearance distributions determined the required bias change. Unfortunately, this procedure creates a nuisance wave-off problem in which some passes are wave-off unnecessarily. Assuming that the bias must be raised by an amount X, the nuisance wave-off rate is composed of that portion of the distribution which is contained between 10 feet and 10 + X feet. For large ramp motions, a substantial portion of the distribution is contained within this range. A quantiative summary of the effects of biasing the wave-off boundary is provided by table VIII.

The results appearing in table VIII indicate a substantial nuisance wave-off rate for the larger ramp motion amplitudes. However, the normal wave-off rate under such high sea states may already be large so that the increment in the wave-off might not be as significant as it would appear from this analysis.

III. RESULTS

The probability of a ramp strike with various deck motion amplitudes and the effects of raising the wave-off boundary are summarized in tables VI to VIII. Because the statistical model analyzed does not correspond exactly to the actual carrier landing situation, the ramp strike rates will not agree necessarily with operational data. However, the analysis was intended to be evaluated on a comparative basis only. Table VII shows that the probability of a ramp strike with 20 feet of deck motion is 6 times as great as the probability for a steady deck. Lesser amplitudes of ramp motion produce a similar, although less pronounced, increase in the ramp strike rate. Six feet of ramp motion, which is a fairly moderate amount, will produce sufficient errors in the WOAS to nearly double the ramp strike rate. This increase in the ramp strike rate would appear to be unacceptable.

Analysis of the boundary bias concept confirmed the results that might have been reasonably expected based on physical reasoning; i.e., the only way to absolutely preclude the possbility of a ramp strike by biasing the wave-off boundary when the deck is pitching is to elevate the wave-off boundary by an amount equal to the ramp excursion. This may be an acceptable procedure for moderate amounts of deck motion. However, the resultant nuisance wave-off rate becomes significant for large deck excursions. For the 20 foot excursion case, 9 percent of the passes were waved-off unnecessarily. This meant that the wave-off rate was 10 times as great as it should have been under the conditions established for the analysis. Therefore, although boundary biasing cannot be completely excluded from consideration, its usefulness is probably limited to moderate deck motion amplitudes. This leads to the conclusion that alternative methods of correcting for deck motion should be investigated. It appears that only a true deck motion prediction system could compensate for deck motion without introducing undesirable factors such as an increased wave-off rate. To function satisfactorily, such a system would have to anticipate the deck position when the aircraft crossed the ramp. The amount of lead time generated would have to be great enough so that the deck position could be predicted at the instant the wave-off command would have to be given under the most severe sea state conditions.

IV. CONCLUSIONS AND RECOMMENDATIONS

Based on the analysis performed for this study the following conclusions are drawn:

a. Uncompensated ramp motion introduces a significant error in the calculated ramp clearance. This may increase the number of ramp strikes unless corrective action is taken by the pilot, LSO, and/or WOAS.

b. Using the boundary bias technique to correct for ramp motion necessitates raising the criterion boundary by an amount approximately equal to the amplitude of the ramp motion. If this is done, there are a substantial number of nuisance wave-offs generated by the WOAS. This is undesirable and may be unacceptable for large deck excursions.

Deck Motion Prediction (DMP) would be the ideal method of correcting for ramp motion. The possibility of a ramp strike due to errors in the WOAS would be greatly reduced if DMP functioned properly. Some corrective measures appear desirable and, since several proposed DMP systems have some reasonable chance of working properly, it is recommended that the proposed Deck Motion Prediction Systems should be thoroughly analyzed to determine if they can function as intended. The following procedure is suggested as a method of analyzing the Deck Motion Prediction Systems:

(1) Collect additional statistics on carrier deck motion. In order to perform a thorough analysis of the deck motion problem, it would be desirable to determine how frequently a given maximum

amplitude of ramp motion occurs. This would permit an evaluation of typical ramp motion occurring during carrier operations.

(2) Obtain representative data for carrier approach trajectories. Data for several different aircraft would be desirable to thoroughly investigate the type and magnitude of the errors in speed, altitude, and glide slope which develop during carrier approaches.

(3) Construct a time history computer model of the WOAS and the Deck Motion Prediction Systems. Accurate models of the aircraft, the carrier motion, and the turbulence and burble should be used. Measurement noise and computational round off in the computer should also be simulated.

(4) All of the Proposed Deck Motion Prediction Systems should be evaluated to determine accuracy potential and prediction time capability. Particular attention should be paid to severe ramp motion situations and high aircraft sink rate cases. These cases will require the highest prediction time in order for the system to function satisfactorily. This analysis should definitely establish how well the WOAS and the DMP will function in realistic fleet operational conditions.

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b. Williams, Warren J., Statistical Presentation of Landing Parameters for Models A-3B, A-6A, A-7A, F-4B and RA-5C Aircraft Aboard the USS Constellation (CVA-64) in the Gulf of Tonkin (Yankee Station) (Survey 22), NADC-ST-7003, 9 October 1970

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TABLE I

AGGREGATE APPROACH STATISTICS
DERIVED FROM THE F-4 AND A-7:
APPLIED TO THE F-8

Variable	$\bar{X}$	σ_X
Range (Ft)	910.0	0.0
Altitude (Ft)	68.8	9.0
Airspeed $\frac{Ft}{Sec}$	236.0	5.5
Sink Rate $\frac{Ft}{Sec}$	13.4	2.5

TABLE II
STEADY DECK AIRCRAFT RAMP
CLEARANCE FOR A MEAN INITIAL
ALTITUDE OF 68.8 Ft.

Ramp Clearance in (Ft)	Probability
-30, 0	0.0003107
0, 10	0.002529
10, 20	0.015209
20, 30	0.05547
30, 40	0.136469
40, 50	0.2322
50, 60	0.34569
60, 70	0.145939
70, 80	0.04808
80, 90	0.0164039
90, 120	0.00172

TABLE III
AIRCRAFT RAMP CLEARANCE
DISTRIBUTION WITH 6 Ft.
DECK MOTION

Ramp Clearance (Ft.)	Probability
-40, -20	0.000101137
-20, -10	0.00013
-10, 0	0.00034608
0, 10	0.004196
10, 20	0.01677369
20, 30	0.057009
30, 40	0.13458
40, 50	0.2432589
50, 60	0.30967
60, 70	0.164297
70, 80	0.0531148
80, 120	0.019299

TABLE IV
AIRCRAFT RAMP CLEARANCE
DISTRIBUTION WITH 12 FT.
DECK MOTION

Ramp Clearance (Ft)	Probability
-50, -30	0.000986
-30, -10	0.0044277
-10, 0	0.01077
0, 10	0.041896
10, 20	0.10697
20, 30	0.1871
30, 40	0.2539136
40, 50	0.22015
50, 60	0.1169
60, 70	0.0348
70, 80	0.00988
80, 120	0.00353

TABLE V
AIRCRAFT RAMP CLEARANCE
DISTRIBUTION WITH 20 FT.
DECK MOTION

Ramp Clearance (Ft)	Probability
-50, -30	0.001468
-30, -10	0.0074825
-10, 0	0.0164549
0, 10	0.0499
10, 20	0.11151
20, 30	0.190924
30, 40	0.2402
40, 50	0.20701
50, 60	0.10512
60, 70	0.051348
70, 80	0.01455
80, 120	0.005677

TABLE VI
RAMP CLEARANCE STATISTICS

Probability	0 Ft.	Maximum Ramp Motion		
		6 Ft.	12 Ft.	20 Ft.
P (Z < 0)	.0003107	.000577	.000834	.001864
P (Z < 10)	.0028397	.0047732	.00549	.008601

TABLE VII
PROBABILITY OF A RAMP STRIKE WITH RAMP
MOTION RELATIVE TO THE PROBABILITY WITH A STEADY DECK

Relative Probability	Steady Deck	6 Ft. Motion	12 Ft. Motion	20 Ft. Motion
P (Z < 0) Moving Deck / P (Z < 0) Steady Deck	1.0	1.85	2.68	6.0
P (Z <10) Moving Deck / P (Z <10) Steady Deck	1.0	1.68	1.93	3.03

TABLE VIII
WAVE-OFF BOUNDARY
BIAS SUMMARY

	Steady Deck	6 Ft. Motion	12 Ft. Motion	20 Ft. Motion
Wave-Off Boundary Elevation Required	0	7.7 Ft.	9.2 Ft.	20 Ft.
Percentage of Nuisance Wave-Offs with Bias	0	1.29%	1.75%	9%
[Percentage of Nuisance Wave-Offs / Percentage of Required Wave-Offs]	0	2.7	3.2	10.5

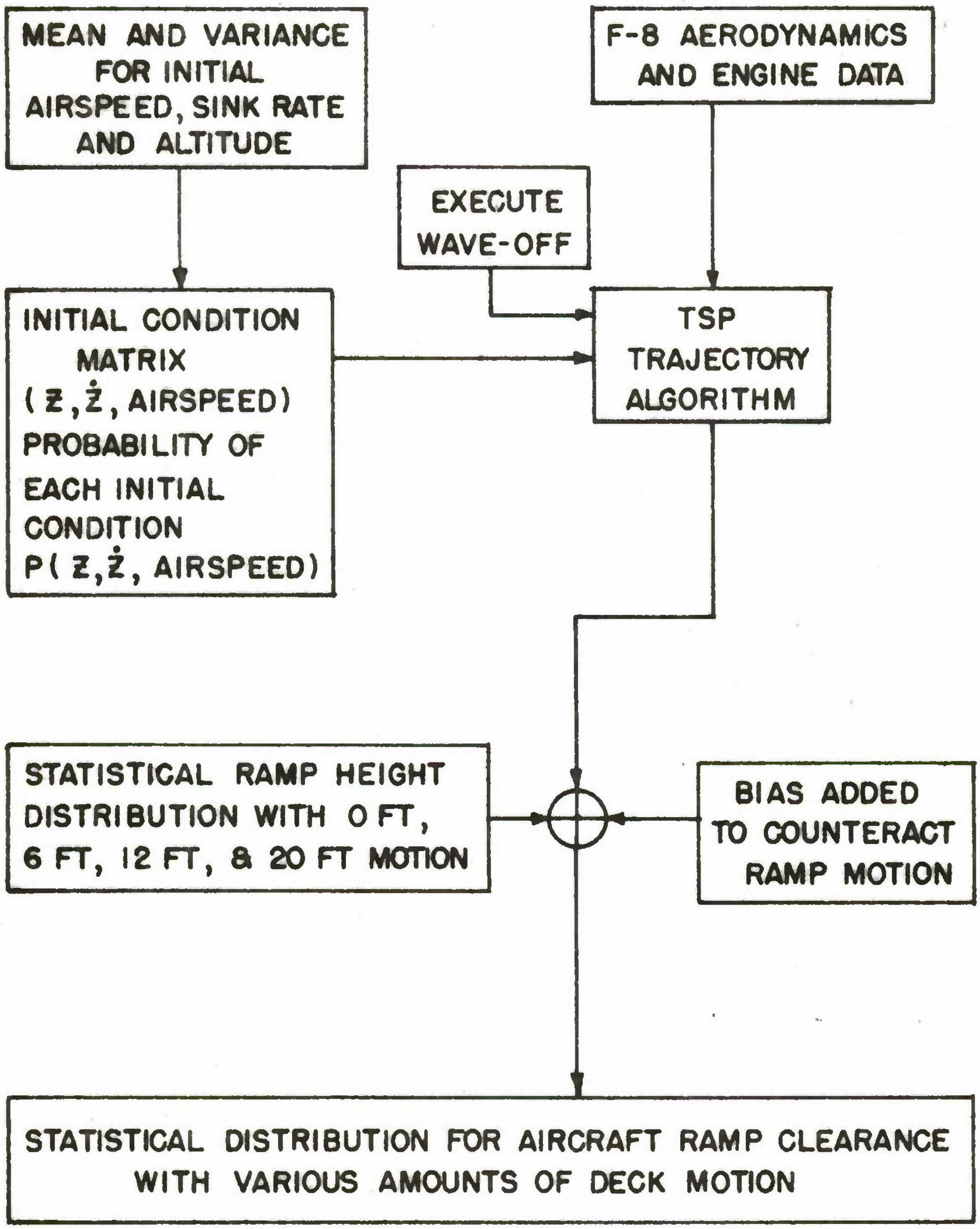


FIGURE 1: STATISTICAL ANALYSIS BLOCK DIAGRAM.

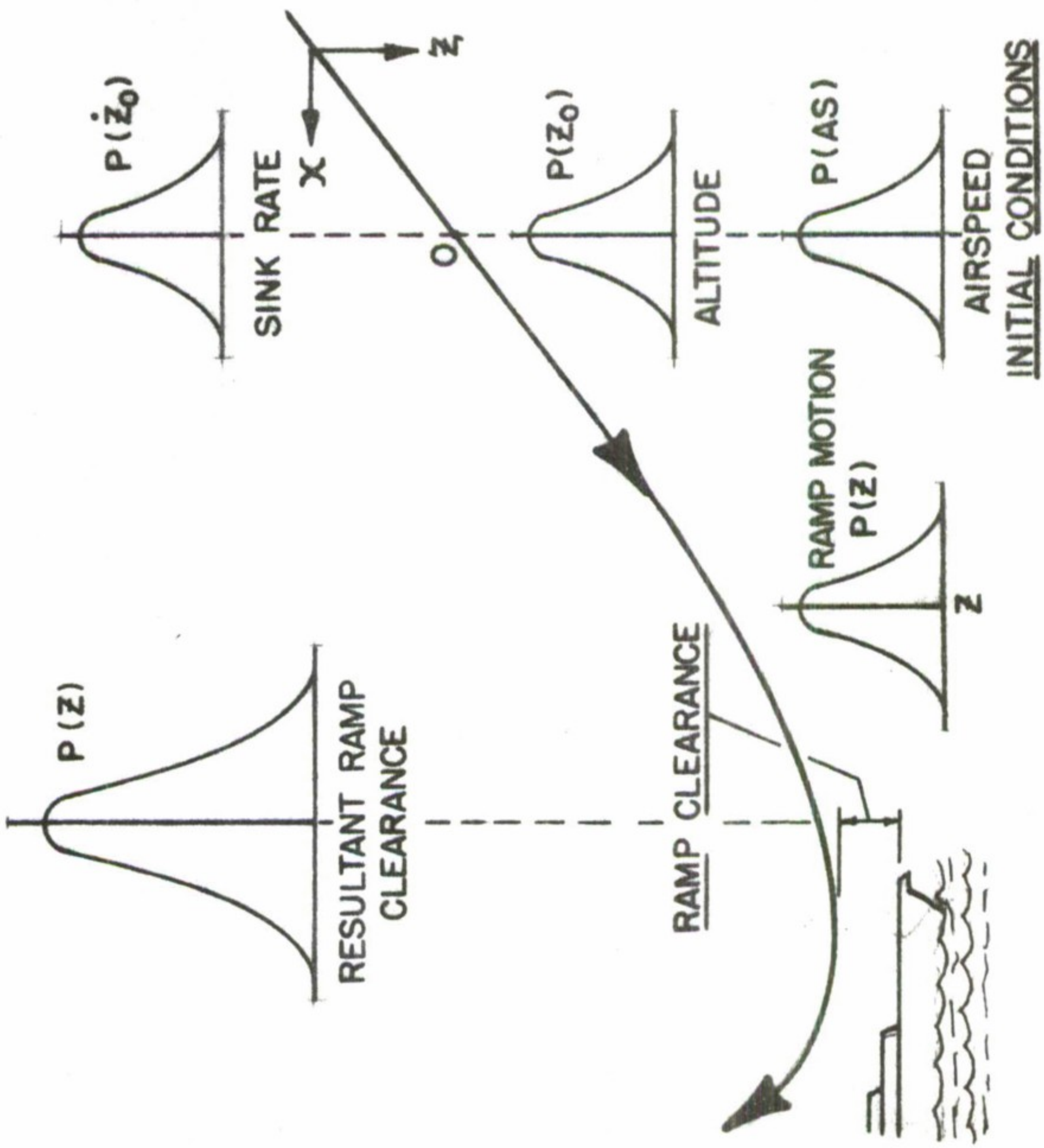
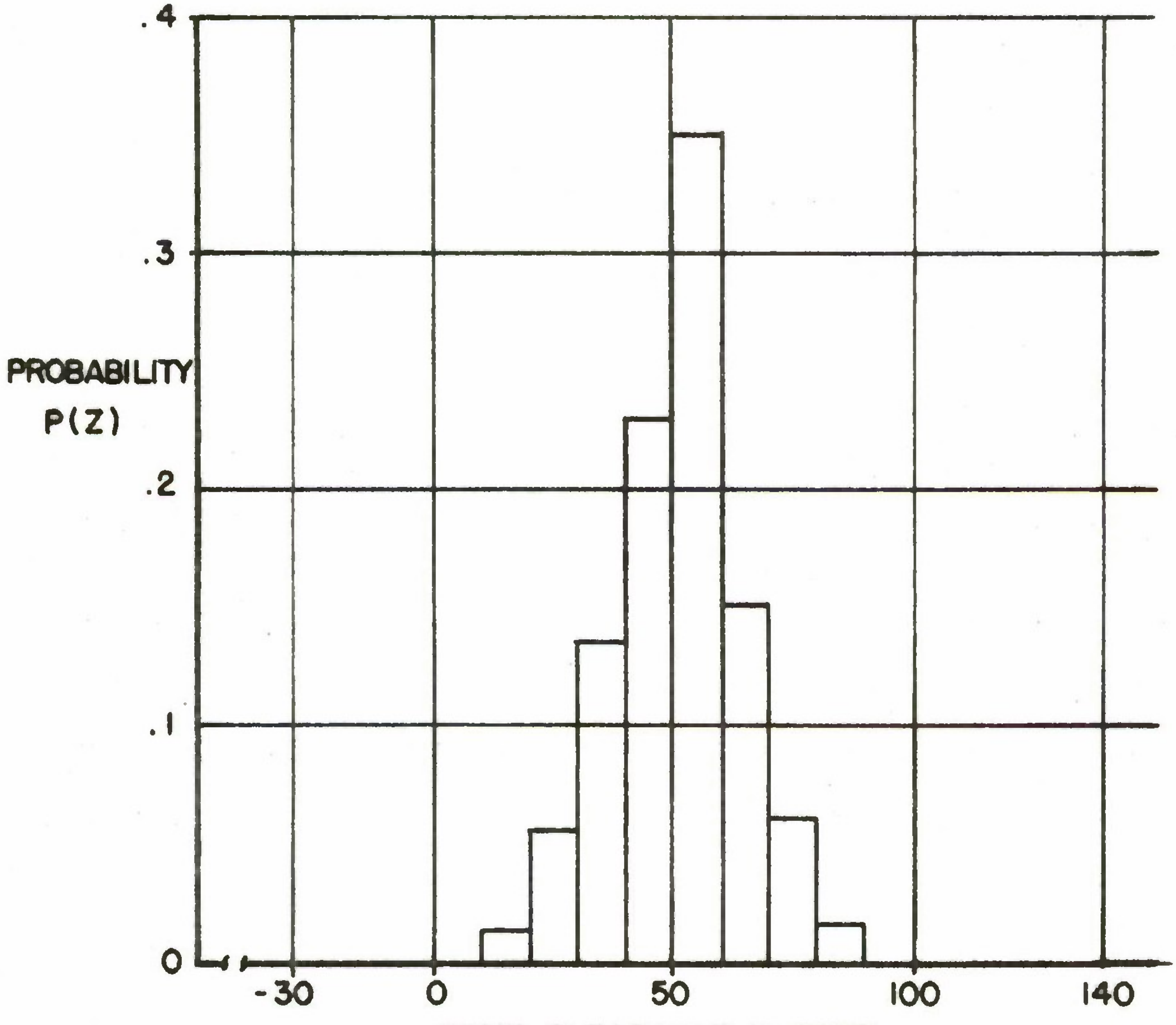


FIGURE 2: AIRCRAFT APPROACH GEOMETRY



$\overline{Z_o}$ = 68.8 FT., $\overline{\dot{Z}_o}$ = 13.4 FT./SEC., $\overline{A/S_o}$ = 236. FT./SEC.

FIGURE 3: AIRCRAFT RAMP CLEARANCE WITH FIXED DECK.

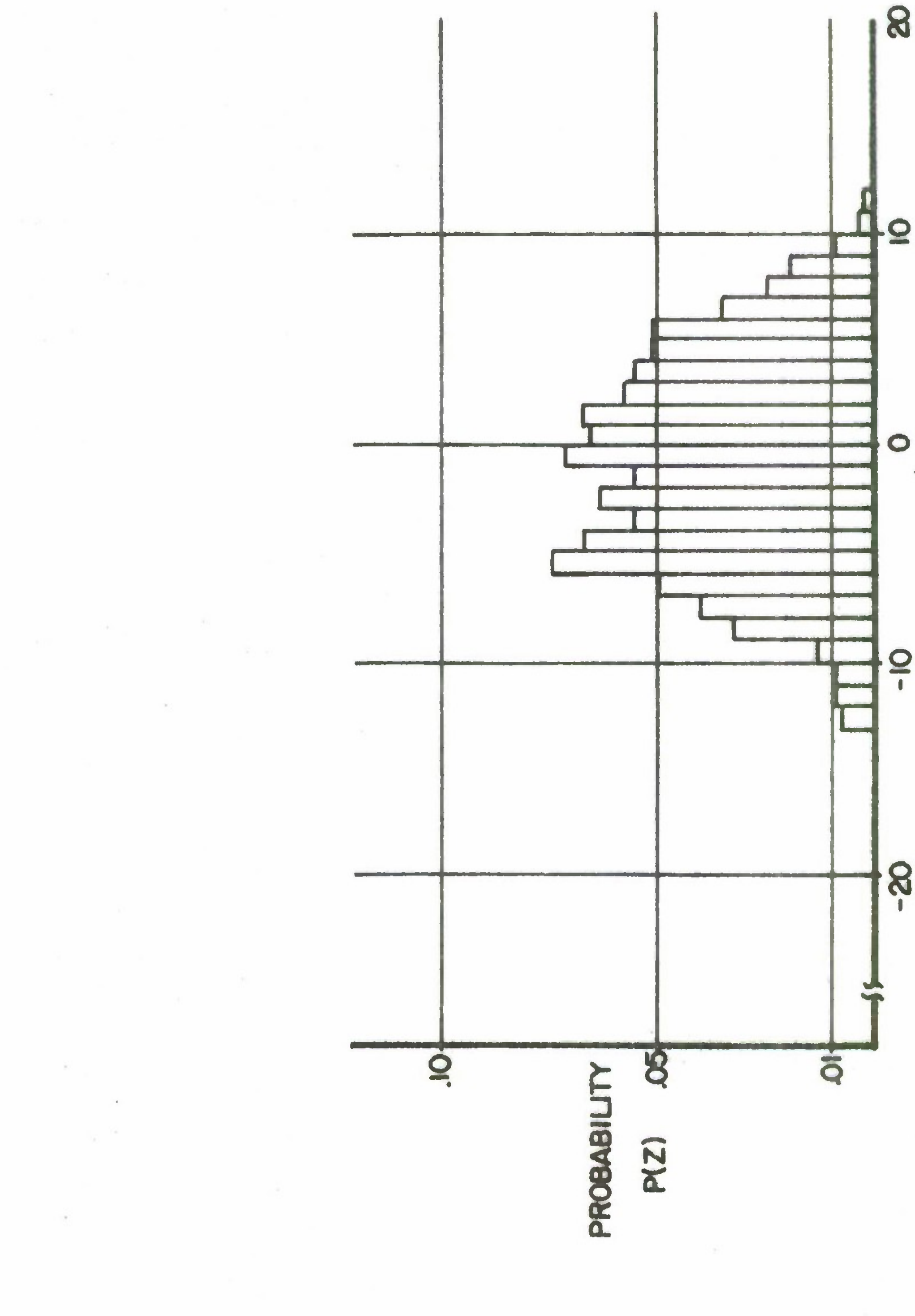


FIGURE 4 : DISTRIBUTION OF RAMP HEIGHT MEASURED FROM MEAN FOR STI CASE # 17.

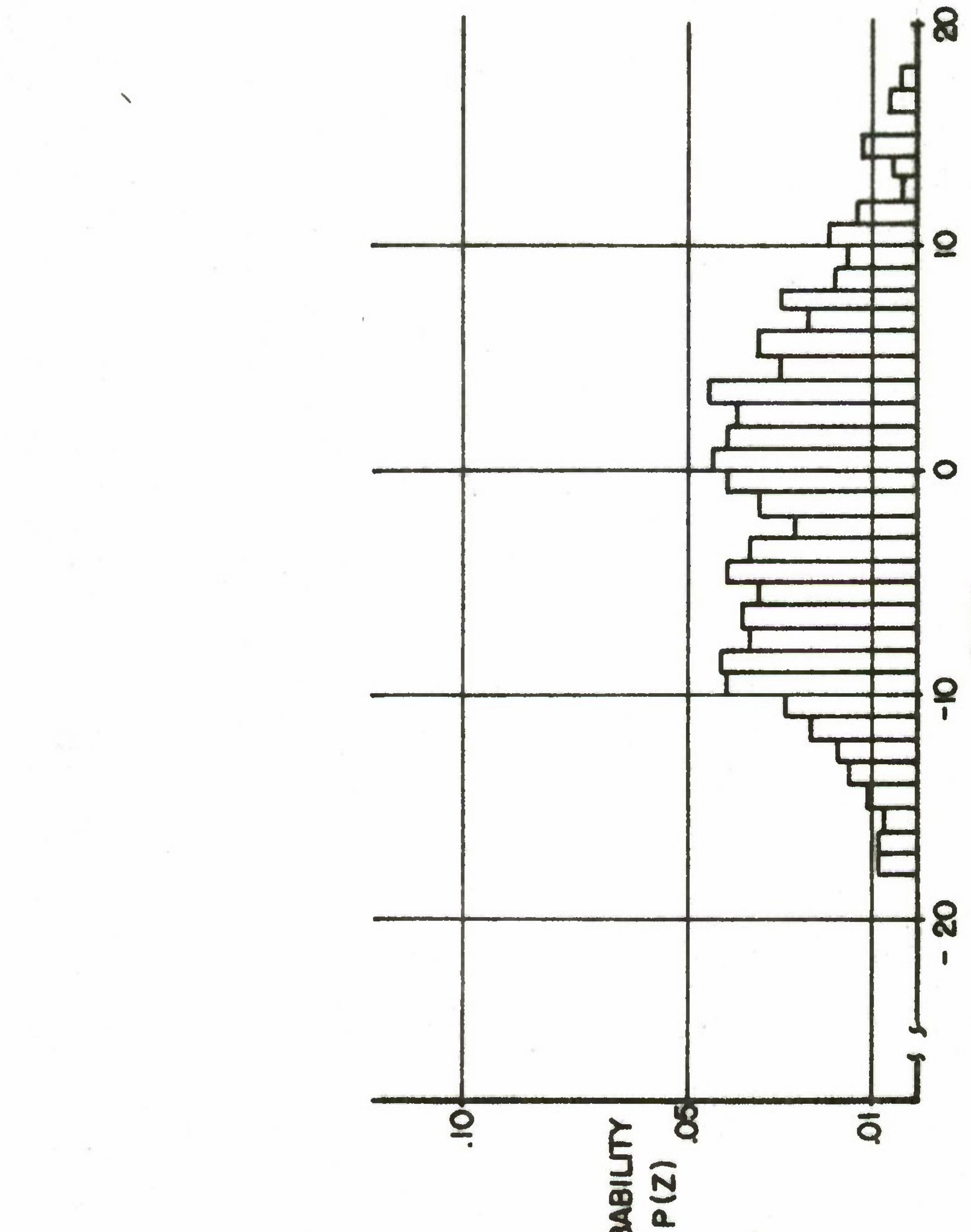


FIGURE 5: DISTRIBUTION OF RAMP HEIGHT MEASURED FROM MEAN FOR STI CASE # 20.

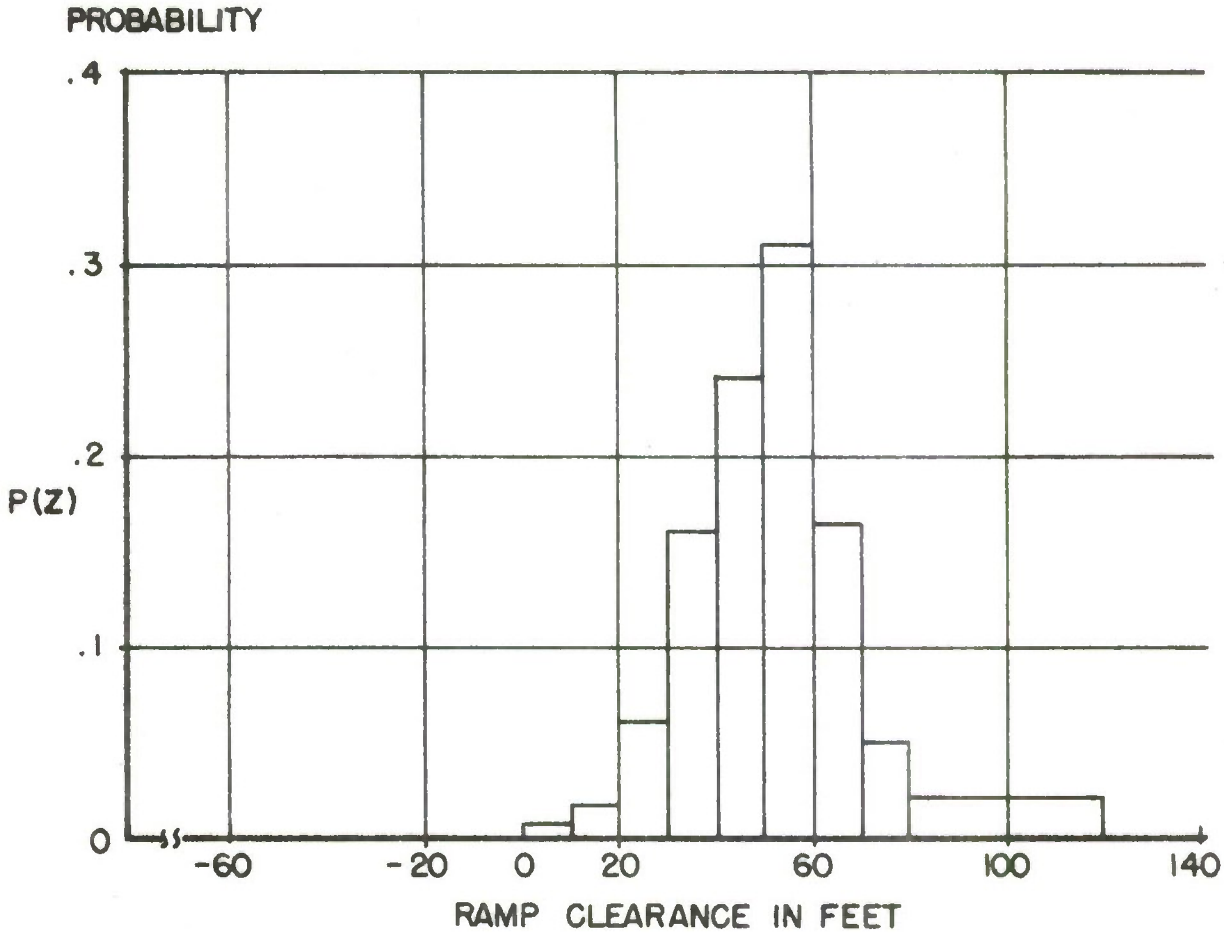


FIGURE 6 : AIRCRAFT RAMP CLEARANCE WITH 6 FT. DECK MOTION.

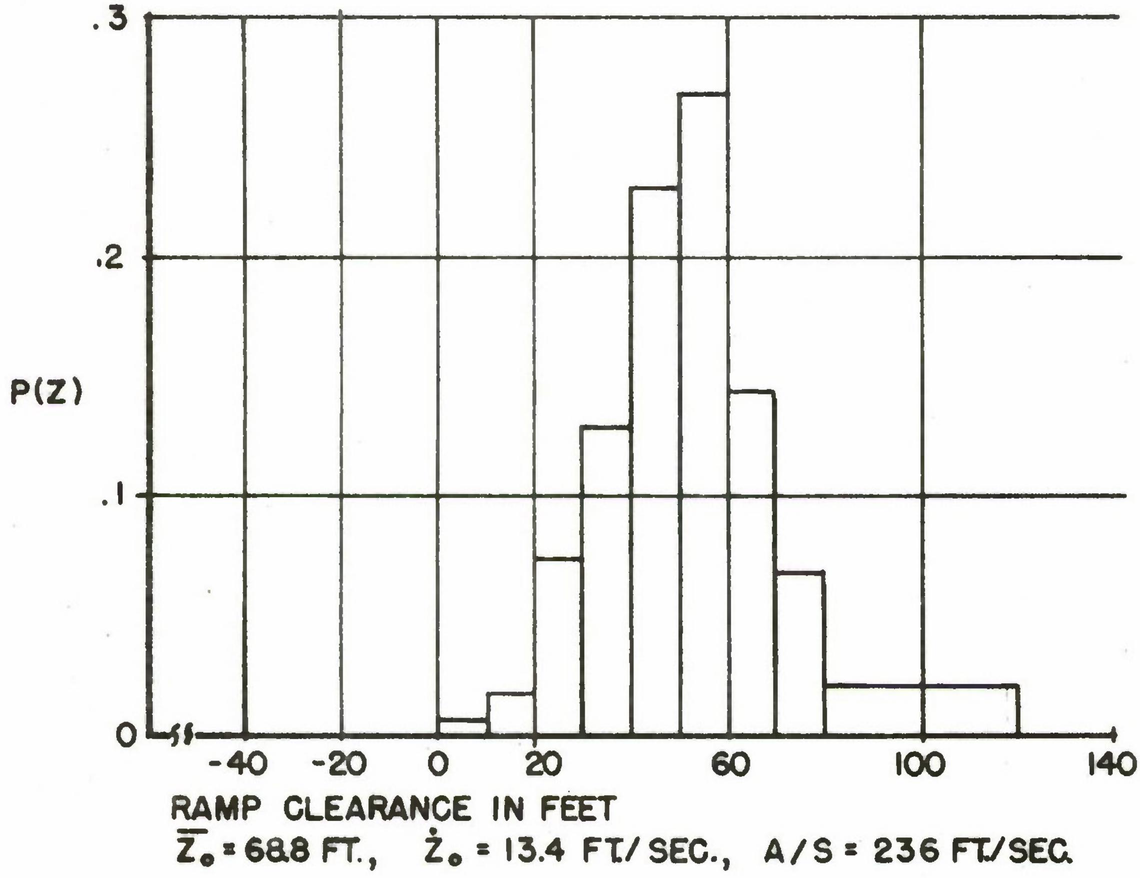


FIGURE 7: AIRCRAFT RAMP CLEARANCE WITH # 17 STI RAMP MOTION.

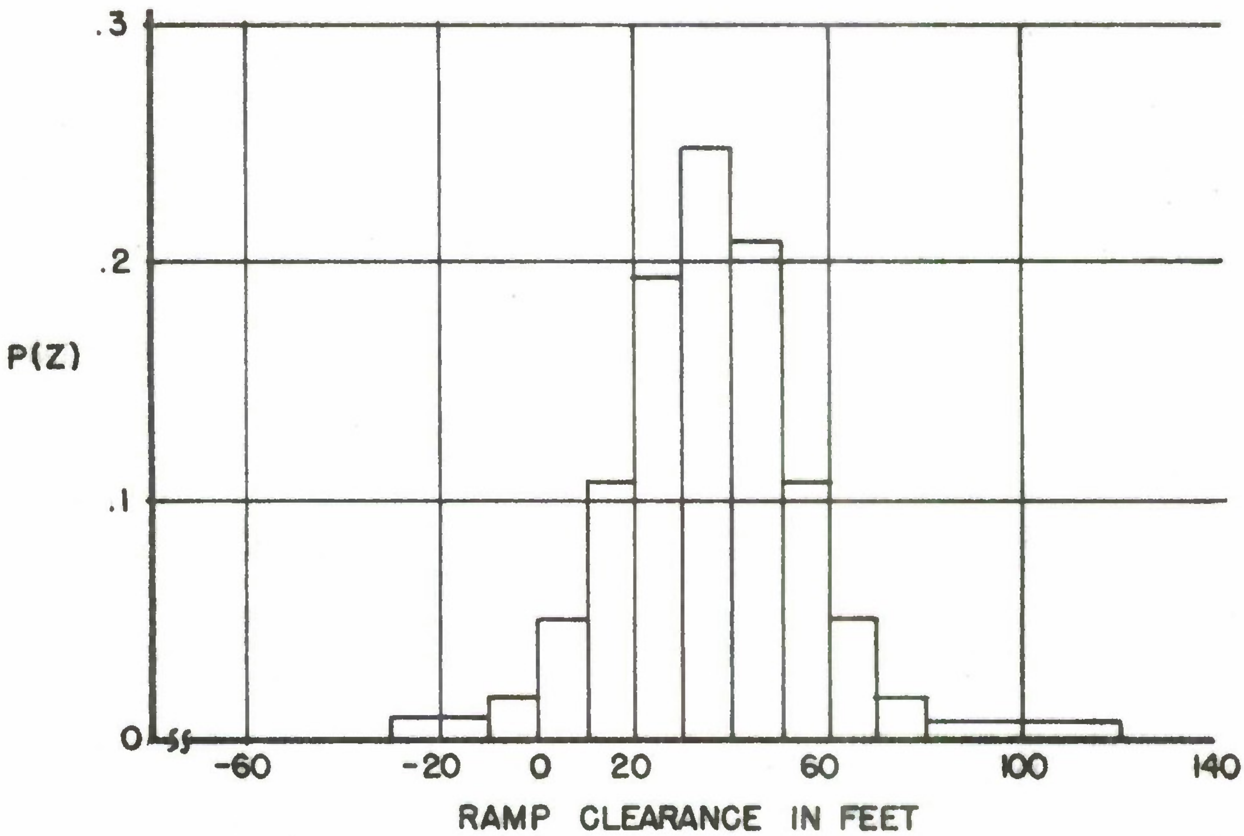


FIGURE 8: AIRCRAFT RAMP CLEARANCE WITH #20 STI RAMP MOTION.

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13. ABSTRACT

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Wave-Off Advisory System Carrier Recovery Deck Motion Prediction						

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